Towards a native toplevel for the OCaml language

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Abstract

This paper presents the current state of our work on an interactive toplevel for the OCaml language based on the optimizing native code compiler and runtime. Our native toplevel is up to 100 times faster than the default OCaml toplevel, which is based on the byte code compiler and interpreter. It uses Just-In-Time techniques to compile toplevel phrases to native code at runtime, and currently works with various Unix-like systems running on x86 or x86-64 processors.

1 Introduction

The OCaml [17, 32] system is the main implementation of the Caml language [6], featuring a powerful module system combined with a full-fledged object-oriented layer. It ships with an optimizing native code compiler ocamlopt, for high performance; a byte code compiler ocamlc and interpreter ocamlrun, for increased portability; and an interactive top-level ocaml based on the byte code compiler and runtime, for interactive use of OCaml through a read-eval-print loop.

ocamlc and ocaml translate the source code into a sequence of byte code instructions for the OCaml virtual machine ocamlrun, which is based on the ZINC machine [16] originally developed for Caml Light [18]. The optimizing native code compiler ocamlopt produces fast machine code for the supported targets (at the time of this writing, these are Alpha, ARM, Itanum, Motorola 68k, MIPS, PA-RISC, PowerPC, Sparc, and x86/x86-64), but

is currently only applicable to *static program com*pilation. For example, it cannot yet be used with multi-stage programming in MetaOCaml [34, 35], or the interactive toplevel ocaml.

This paper presents our work¹ on a new native OCaml toplevel, called ocamlnat, which is based on the native runtime, the compilation engine of the optimizing native code compiler and an earlier prototype implementation of a native toplevel by Alain Frisch. Our implementation currently supports x86 and x86-64 processors [1, 10] and should work with any POSIX compliant operating system supported by the OCaml native code compiler. It is verified to work with Mac OS X 10.6 and 10.7, Debian GNU/Linux 6.0 and above, and CentOS 5.6 and 5.7. The full source code is available from the ocamljit-nat branch of the ocaml-experimental Git repository hosted on GitHub at [28].

The paper is organized as follows: Section 2 motivates the need for a usable native OCaml toplevel. Section 3 presents an overview of the OCaml compilers and Section 4 describes the previous ocamlnat prototype which inspired our work, while Section 5 presents our work on ocamlnat. Performance measures are given in Section 6. Sections 7 and 8 conclude with possible directions for further work.

2 Motivation

Interactive toplevels are quite popular among dynamic and scripting languages like Perl, Python, Ruby and Shell, but also with functional programming languages like OCaml, Haskell and LISP. In

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¹The initial work in this area was done as part of the first author's diploma thesis.

case of scripting languages the interactive toplevel is usually the only frontend to the underlying interpreter or Just-In-Time compiler.

In case of OCaml, the interactive toplevel is only one possible interface to the byte code interpreter; it is also possible to separately compile source files to byte or native code object files, link them into libraries or executables, and deploy these libraries or executables. The OCaml toplevel is therefore mostly used for interactive development, rapid prototyping, teaching and learning, as an interactive program console or for scripting purposes.

The byte code runtime is the obvious candidate to drive the interactive toplevel, because the platform independent byte code is very portable and easy to generate – compared to native machine code. And in fact the byte code toplevel has served users and developers well during the last years. But nevertheless there are valid reasons to have a native code toplevel instead of or in addition to the byte code toplevel:

Performance This is probably the main reason why one wants to have a native code toplevel. While the performance of the byte code interpreter is acceptable in many cases (which can be improved by using one of the available Just-In-Time compilers [27, 26, 29, 33]), it is not always sufficient to handle the necessary computations. Sometimes one needs the execution speed of the native runtime, which can be up to hundred times faster than the byte code runtime as we will show in Section 6.

For example, the Mancoosi project [24] has developed a library that allows to perform analysis of large sets of packages in free software distributions, that can be done acceptably efficiently with the native code compiler and runtime, but are too slow in bytecode. To perform interactive analysis (i.e. select packages with particular properties, analyse them, ...), having a native toplevel is really the only way to go for them, as it can combine the flexibility of the toplevel interaction with the speed of native code.

Tools such as ocamlscript [25] try to combine the performance of the code generated by the optimizing native code compiler with the flexibility of a "scripting language interface". But this is basically just a work-around – with several limitations. A native toplevel would address this issue in a much

cleaner and simpler way.

Native runtime There are scenarios where only the native code runtime is available and hence the byte code toplevel, which depends on the byte code runtime, cannot be used. One recent example here is the Mirage cloud operating system [21, 22, 23], which compiles OCaml programs to Xen microkernels [4] and executes them via the Xen hypervisor [38]. Mirage uses the OCaml toplevel as OS console, but is currently limited to the byte code toplevel in read-only mode, due to the lack of a toplevel that works with the native code runtime.

3 Overview of the OCaml compilers

In this section we briefly describe the OCaml compilers, covering both the byte code compiler ocamlc and the optimizing native code compiler ocamlopt. Feel free to skip to section 4 if you are already familiar with the details.

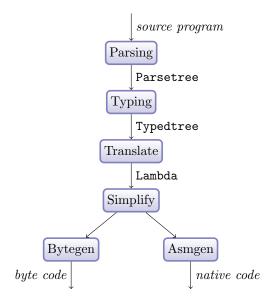


Figure 1: The OCaml compilers

Figure 1 gives an overview of the compiler phases and representations in the OCaml byte and native code compilers. Compilation always starts by parsing an OCaml source program (either from a source file or a source region in interactive mode) into an abstract syntax tree (AST, see file parsing/parsetree.mli of the OCaml source code). Compilation then proceeds by computing the type annotations to produce a typed syntax tree (see file typing/typedtree.mli).

From this typed syntax tree, the compiler generates a so called lambda representation (see file bytecomp/lambda.mli) inspired by the untyped call-by-value λ -calculus [3, 11, 30]. This lambda representation is then optimized by transforming lambda trees into better or smaller lambda trees (see file bytecomp/simplif.ml), yielding a final platform independent, internal representation of the source program as result of the compiler frontend phases.

The simplified lambda representation is then used as input for the respective compiler backend, which is either

- the Bytegen module in case of the byte code compiler (see file bytecomp/bytegen.ml), or
- the Asmgen module in case of the optimizing native code compiler (see file asmcomp/asmgen.ml).

The byte code backend, which is used by the byte code compiler ocamlc as well as the byte code toplevel ocaml, basically transforms the simplified lambda representation into an equivalent byte code program (see file bytecomp/instruct.mli), suitable for (a) direct execution by the byte code interpreter ocamlrun or (b) just-in-time compilation using either OCAMLJIT [33] or OCamlJIT2 [26, 27, 29]. This is done by the Emitcode module (see file bytecomp/emitcode.ml). Additional details about the byte code compiler and runtime can be found in [16], [27] and [33].

The native code backend, which is used by the optimizing native code compiler ocamlopt as well as the native toplevel ocamlnat, is shown in Figure 2. It takes the simplified lambda representation as input and starts by transforming it into a variant of the lambda representation (see file asmcomp/clambda.mli) with explicit closures and explicit direct/indirect function calls (see file asmcomp/closure.ml). This is then further processed and transformed into an equivalent representation in an internal dialect of C-- [12, 13] (see

files asmcomp/cmm.mli and asmcomp/cmmgen.ml).

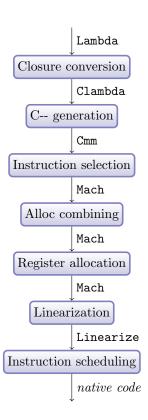


Figure 2: Native code generation (Asmgen module)

Afterwards the Instruction selection phase (see file asmcomp/selection.ml) picks appropriate instructions for the target machine, transforming the C-- code into a tree based representation of the machine code (see file asmcomp/mach.mli). The next step attempts to combine multiple heap allocations within a basic block into a single heap allocation (see file asmcomp/comballoc.ml), prior to allocating and assigning physical registers to the virtual registers used in the machine code (see function regalloc in file asmcomp/asmgen.ml). The final phases linearize the machine code (see file asmcomp/linearize.ml) and perform instruction scheduling for better performance (see file asmcomp/scheduling.ml), yielding the final representation of the (linearized) machine code.

The optimizing native code compiler ocamlopt writes the linearized machine code output of the

Asmgen module to an assembly file in the appropriate format for the target platform (see file asmcomp/emit.ml), i.e. using AT&T assembly syntax on Linux and Mac OS X while using Intel assembly syntax on Windows, and invokes the assembler from the system compiler toolchain, i.e. GNU as on Linux, to generate an object file. This object file can then be linked with other OCaml modules and C code into an executable binary or a dynamic library file.

4 The native toplevel

In 2007 Alain Frisch added support for the Dynlink library to the native code compiler and runtime, which was first made available as part of OCaml 3.11. This change made it possible to use the OCaml native code runtime with dynamically loaded plugins, a feature that was previously only available with the byte code runtime. Besides various other benefits, this also made it possible to reuse the existing functionality of the optimizing native code compiler within the scope of a native toplevel.

The initial proof-of-concept prototype of a native toplevel, developed by Alain Frisch and named ocamlnat, was since then silently shipped with every OCaml source code release².

Figure 3 gives an overview of the internals of this ocamlnat prototype. It works by starting up the OCaml native runtime and then prompts the user for OCaml phrases to evaluate (just like the byte code toplevel ocaml does). Whenever the user enters a phrase, it is compiled to native code using the modules of the optimizing native code compiler (utilizing the frontend phases as shown in Figure 1 and the native backend phases as shown in Figure 2).

This native code is written to a temporary assembly file by the Native code emitter, which is also part of ocamlopt. The assembly file is then passed to the Toolchain Assembler, i.e. GNU as on Linux, to produce a temporary object file. This object file is afterwards turned into a dynamic library file by the Toolchain Linker, i.e. GNU 1d on Linux, and loaded into the native toplevel process using

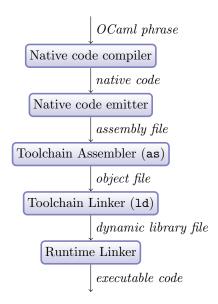


Figure 3: ocamlnat prototype

the Runtime Linker, finally yielding a memory area with the *executable code* which is then executed.

While this approach has the immediate benefit of requiring only a few hundred lines of glue code to turn the existing modules of the optimizing native code compiler and the native Dynlink library into a native toplevel, there are also several obvious drawbacks to this approach – preventing widespread adoption of ocamlnat:

Dependency on the system toolchain This is the most important problem of the native toplevel prototype as it prevents from being used in areas that would really benefit from a native toplevel but do not have the toolchain programs available. For example, the Mirage cloud operating system [21, 22, 23] compiles OCaml programs to Xen micro-kernels, which are then executed by the Xen hypervisor [38]; Mirage uses the OCaml toplevel as OS console, but is limited to the byte code toplevel in read-only mode right now, as there is obviously no GNU toolchain available in a Xen micro-kernel.

It is worth noting that the toolchain dependency is also a problem with the optimizing native code compiler ocamlopt on certain platforms such as Microsoft Windows where it is often a non-trivial

²It must be build explicitly using make ocamlnat after make world and make opt, and it is only available for targets that support the native Dynlink library.

task to install the system toolchain. This is one of the reasons why companies such as LexiFi provide custom OCaml distributions with an integrated toolchain.

Latency While the latency caused by reading and writing the assembly, object and library files as well as invoking the external toolchain programs is not necessarily a show-stopper for an interactive toplevel, it is nevertheless quite noticable, especially with short running programs or programs with many phrases, as we will see in Section 6.

Temporary library files On Microsoft Windows it is impossible to delete a library file that is currently loaded into a process, which means that the prototype "leaks" one library file per toplevel phrase.

Unclear maintenance status Many people don't even know about ocamlnat, and those who do cannot rely on it. This is because ocamlnat is not part of an OCaml installation, even though it ships as part of the source code distribution, and it is not documented anywhere.

This is not so much a technical argument against the current approach, but it highlights its status as being a proof-of-concept with no clear direction from the users point of view.

5 Just-In-Time code generation

We aim to improve ocamlnat in a way that avoids the drawbacks of the earlier prototype and turns the native toplevel into a viable alternative to the byte code toplevel. As noted above, the major drawback of Alain's prototype is the dependency on the system toolchain, that is, the external assembler and linker programs.

Therefore we had to replace the last four phases of the ocamlnat prototype (as shown in Figure 3) with something that does not depend on any external programs but does the executable code generation just-in-time within the process of the native toplevel.

Figure 4 shows our current implementation. We replaced the Native code emitter and Toolchain As-

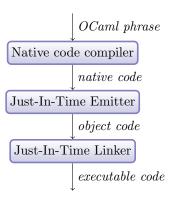


Figure 4: ocamlnat overview

sembler phases from the ocamlnat prototype with a Just-In-Time Emitter phase, and the Toolchain Linker and Runtime Linker phases with a Just-In-Time Linker phase. The earlier phases, that are shared with the optimizing native code compiler ocamlopt as described in Section 3 and 4, remain unchanged.

The Just-In-Time Emitter phase is responsible for transforming the linearized native code that is generated by the Native code compiler (as shown in Figure 2) into object code for the target platform. This object code is very similar to the object file generated by the Toolchain Assembler; it contains a text section with the executable code, a data section with the associated data items (i.e. the floating-point constants, closures and string literals used within the code, the frametable for the garbage collector, ...), a list of relocations, and a list of global symbols.

The Just-In-Time Linker phase allocates executable memory for the text section and writable memory for the data section, copies the section contents to their final memory locations, takes care of the relocations, and registers the global symbols. This is roughly what the Toolchain Linker and Runtime Linker in the ocamlnat prototype do.

The code for the two phases is found in the toplevel/jitaux.ml file, which provides the common, platform independent functionality for Just-In-Time code generation, as well as toplevel/amd64/jit.ml for the x86-64 platform and toplevel/i386/jit.ml for the x86 platform, plus a few lines of additional C code in asmrun/natdynlink.c and asmrun/natjit.c. At the time of this writing the changes for our new native toplevel with support for x86 and x86-64 account for approximately 2300 lines of C and OCaml code as shown in Table 1.

	OCaml	\mathbf{C}
Generic	277	185
amd64	863	
i386	991	/
	2131	185

Table 1: Additional lines of code for ocamlnat

We tried to keep the code as easy to maintain as possible. To achieve this goal we

- (a) reused as much of the existing functionality as possible of both the native code compiler and its runtime,
- (b) kept the amount of additional runtime support as low as possible (basically just an additional layer in the global symbol management and a new entry point for the Just-In-Time code execution), and
- (c) made the Just-In-Time Emitter (the jit.ml files in the toplevel subdirectories) look as similar as possible to the Native Code Emitter (the emit.mlp files in the asmcomp subdirectories).

The last point is especially important as every change to the Native Code Emitters (i.e. asmcomp/amd64/emit.mlp) must be reflected by an equivalent change to the appropriate Just-In-Time Emitter (i.e. toplevel/amd64/jit.ml). Fortunately the Native Code Emitters usually do not change very often during the OCaml development process.

6 Performance

We compared the performance of our native toplevel to the performance of the byte code toplevel ocaml running on top of the OCaml 3.12.1 byte code interpreter, the byte code toplevel ocaml running on top of the OCamlJIT2 Just-In-Time byte code compiler [26, 27, 29], and Alain Frisch's

earlier ocamlnat proof-of-concept implementation (as described in Section 4). We measured the performance on four different systems:

- A MacBook Pro 13" (Early 2011) with an Intel Core i7 2.7GHz CPU (4 MiB L3 Cache, 256 KiB L2 Cache per Core, 2 Cores) and 4 GiB RAM, running Mac OS X Lion 10.7.1. The C compiler is 11vm-gcc-4.2.1 (Based on Apple Inc. build 5658) (LLVM build 2336.1.00).
- An iMac 20" (Early 2008) with an Intel Core 2 Duo "Penryn" 2.66GHz CPU (6 MiB L2 Cache, 2 Cores), and 4 GiB RAM, running Mac OS X Lion 10.7.1. The C compiler is 11vm-gcc-4.2.1 (Based on Apple Inc. build 5658) (LLVM build 2336.1.00).
- A Fujitsu Siemens Primergy server with two Intel Xeon E5520 2.26GHz CPUs (8 MiB L2 Cache, 4 Cores), and 12 GiB RAM, running CentOS release 5.7 (Final) with Linux/x86_64 2.6.18-274.3.1.el5. The C compiler is gcc-4.1.2 (Red Hat 4.1.2-51).
- A Fujitsu Siemens Primergy server with an Intel Pentium 4 "Northwood" 2.4 GHz CPU (512 KiB L2 Cache), and 768 MiB RAM, running Debian testing as of 2011/09 with Linux/i686 3.0.0-1-686-pae. The C compiler is gcc-4.6.1 (Debian 4.6.1-4).

The OCaml distribution used for the tests is 3.12.1. The OCamlJIT2 version is the commit 8514ccb from the ocamljit2 Git repository hosted on GitHub at [29]. For our native toplevel ocamlnat we used the commit d30210d from the ocaml-experimental Git repository hosted on GitHub at [28].

The benchmark programs used to measure the performance are the following test programs from the testsuite/test folder of the OCaml 3.12.1 distribution:

almabench is a number-crunching benchmark designed for cross-language comparisons.

bdd is an implementation of binary decision diagrams, and therefore a good test for the symbolic computation performance.

boyer is a term manipulation benchmark.

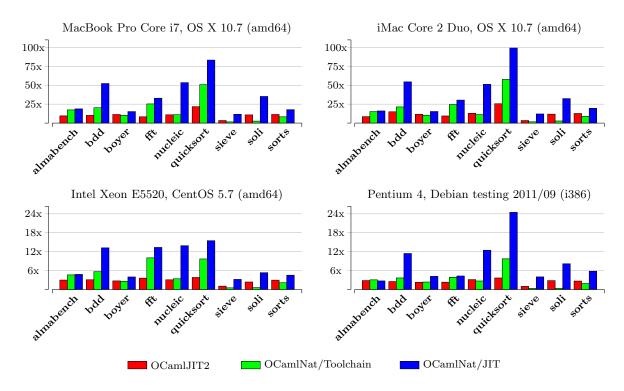


Figure 5: Speedup relative to the byte code toplevel ocaml

fft is an implementation of the Fast Fourier Transformation [5].

nucleic is another floating-point benchmark.

quicksort is an implementation of the well-known QuickSort algorithm [8, 9] on arrays and serves as a good test for loops.

sieve is an implementation of the sieve of Eratosthenes, one of a number of prime number sieves, for finding all prime numbers up to a specified integer.

soli is a simple solitaire solver, well suited for testing the performance of non-trivial, short running programs.

sorts is a test bench for various sorting algorithms.

For our tests we measured the total execution time of the benchmark process itself and all spawned child processes (only relevant for the earlier toolchain based ocamlnat prototype), given as combined system and user CPU time. The times were collected by executing each benchmark two

times with every toplevel, and using the timings of the fastest run.

Figure 5 presents the results of the benchmarks as speedup relative to the regular byte code toplevel ocaml, where OCamlNat/Toolchain is Alain Frisch's toolchain based ocamlnat prototype and OCamlNat/JIT is our new Just-In-Time based native toplevel. As you can see we managed to achieve speedups of up to hundred times faster than the byte code toplevel in certain benchmarks. It is however worth noting that this is in part related to the fact that llvm-gcc became the default C compiler with recent versions of OS X (and it's related software development tools), which disables the very important manual register assignment optimization in the byte code interpreter, because LLVM does not support manual register assignment.

7 Related and further work

We are looking forward to integrate our new native toplevel as interactive console into the Mirage

cloud operating system [21, 22, 23], which will be really useful for development (i.e. when exploring the heap of Xen kernels interactively to find resource leaks, ...).

Right now our ocamlnat implementation supports only x86 and x86-64 targets on POSIX systems. We plan to add support for additional targets that are already supported by the optimizing native code compiler, most notably ARM and PowerPC, and extend the support for other operating systems, i.e. Windows.

We are also working on integrating the linear scan register allocator [31, 37] into the optimizing native code compiler as an alternative to the currently used graph coloring register allocator [2]. By using the linear scan algorithm, which is commonly used in the scope of Just-In-Time compilers, we expect to avoid the quadratic worst case running time of the graph coloring algorithm³.

We are also in the process of evaluating the use of the LLVM compiler infrastructure [14, 15, 19] as a replacement for the last phases of the native code compiler engine. Other projects such as Clang [7], GHC [36] and MacRuby [20] already demonstrated the viability and usefulness of using LLVM as compiler backend. Besides the other obvious benefits of using LLVM in OCaml, we would also get the Just-In-Time compilation and execution engine for free.

8 Conclusion

Our results demonstrate that an OCaml toplevel based on the native code compiler and runtime offers significant performance improvements over the byte code toplevel (at least thrice as fast in all benchmarks, and up to hundred times faster in one benchmark), at acceptable maintenance costs.

As demonstrated in Section 6 we were also able to beat the performance of our earlier byte code based OCamlJIT2 prototype in almost every case (except for the almabench benchmark on x86, which is due to the fact that OCamlJIT2 uses SSE2 registers and instructions while our native toplevel uses the x87 FPU stack and instructions [26]).

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